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PUZZLE PIECES: RESULTS ON $b\bar{b}$ AND $c\bar{c}$ SPECTROSCOPY AND DECAY

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ABSTRACT

Recent results in the field of Heavy Quarkonia are reviewed, with results either providing new precision measurements or addressing key unanswered questions.

1 Introduction

Heavy quarkonia exhibit features similar to the positronium spectrum: a discrete system of states with the spacings and transition rates dictated by the binding force, which in this case is the strong interaction. Investigating heavy quarkonia therefore enables us to study important aspects of QCD. While heavy quarkonia parton level decay by annihilation is a perturbatively calculable process, transitions among them are not as they are soft due to the energy spread between the states, which is below 1 GeV.

Theory has made progress recently that indicates the need for experimental results at the few percent level in precision. On the other hand, there are important unanswered questions where experimental information is scant. The following results have been selected so as to address one or the other.

In view of the very limited space available for this report, no figures are shown, but references to publications where they can be found are given. More $\psi(2S)$ results from BES were presented in a separate talk by X.H. Mo at this conference.

2 Spectroscopy

2.1 Measurements of the η_c' Mass [1]

After the first evidence for the η_c' more than twenty years ago, which established it from the direct M1 transition $\psi(2S) \to \gamma\eta_c'$, the experimental picture has consolidated in the past two years: In $B \to \eta_c' K$, $e^+e^- \to J/\psi\eta_c'$, and $\gamma\gamma \to \eta_c'$ studies, the η_c' mass is found to be around 3638 MeV, or 44 MeV higher than measured before. This means that the 2^3S_1-2^1S_0 mass splitting is reduced by a factor of two, and is now two times smaller than the hyperfine splitting at $n = 1$. Comparing these two is interesting because, due to the difference in $c\bar{c}$ distance, they sample different areas of the binding potential, which connects the confinement region with that of asymptotic freedom.

2.2 $X(3872)$ [2]

Since the discovery of the "$X(3872)$" by Belle and subsequent confirmation by BaBar, CDF, and D0, several attempts to explain this narrow state have been made on the theory side. Among the plausible ones are that it could be a charmonium state, a $D\bar{D}$ molecule, or even an exotic state. Experimental efforts have focussed on studying decay or production modes that can clarify the nature of this state by virtue of establishing its quantum numbers. The decay mode $X \to \pi^+\pi^- J/\psi$, which gives rise to the state's characterization as "charmonium-like", remains the only one seen so far. The dipion mass distribution is of special interest as one hopes to answer the question whether or not the decay proceeds through an intermediate ρ. In this context, searching for $X(3872) \to \pi^0\pi^0 J/\psi$ is of special importance. CLEO has engaged in a search for X(3872) in two-photon fusion and ISR production, using 15 fb^{-1}

of data at $\sqrt{s} = 9.46 - 11.30\,\text{GeV}$. This allows access to $J^{PC} = 1^{--}$ and $2n^{\pm+}$. Preliminary upper limits have been placed: $\Gamma_{ee} \times \mathcal{B}(X \to \pi^+\pi^- J/\psi) <$ $6.8\,\text{eV}$ or 1% of the production rate of $\psi(2S)$ in ISR events (assuming a similar branching fraction $\mathcal{B}_{\pi^+\pi^- J/\psi}$), and $(2J+1)\Gamma_{\gamma\gamma} \times \mathcal{B}(X \to \pi^+\pi^- J/\psi) < 16.7\,\text{eV}$, or one tenth of the η_c production rate in two-photon fusion. A similar ISR study has been done of BES data, using using $22.3\,\text{pb}^{-1}$ at $\sqrt{s} = 4.03\,\text{GeV}$, which arrived at an upper limit of $\Gamma_{ee} \times \mathcal{B}(X \to \pi^+\pi^- J/\psi) < 10\,\text{eV}$.

2.3 Transitions [3)]

Transitions between states of heavy onia are by emission of photons or hadrons such charged pion pairs, neutral single pions or pion pairs, and etas. In bottomonium, also an ω transition has recently been observed as the first non-pionic hadronic transition in $\Upsilon(3S) \to \gamma\chi_{b1,2}(2S)$, $\chi_{b1,2} \to \omega\Upsilon(1S)$. The branching fractions are found to be substantial and also in compliance with a prediction for them to be about equal: $\mathcal{B}(\chi_{b1[2]} \to \omega\Upsilon(1S) = (1.63^{+0.31+0.15}_{-0.32-0.11})$ $[(1.10^{+0.35+0.16}_{-0.28-0.10})]\%$. Radiative decays to Υs are, to date, the only other known exclusive decay mode of the χ_{bJ} states, and are only a factor 5-6 more common.

While η and single π^0 transitions have been seen in charmonium, with recent BES studies showing a much increased precision over previous results, a similar measurement in bottomonium is yet to be made.

Dipion transitions are the most common ones both in $c\bar{c}$ and $b\bar{b}$. Naively, one would expect that the ratio of branching fractions for neutral and charged modes would be, related by isospin, 1:2. A direct measurement of this quantity resulted in $\mathcal{B}(\psi(2S) \to \pi^0\pi^0 J/\psi)/\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi) = 0.570 \pm 0.009 \pm 0.026$; taking the most recent PDG values for the individual branching fractions yields 0.59 ± 0.04. An interesting new measurement has been made by BaBar, using radiative return events to the $\psi(2S)$ in $90\,\text{fb}^{-1}$ of $\Upsilon(4S)$ data. They find $\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi) = 0.361 \pm 0.40$, which decreases the ratio by over 12%, thereby bringing it within reach of 0.5.

3 Decays

3.1 $\psi(3770) \to$ non-$D\bar{D}$? [4)]

The experimental indication for the existence of a significant $\psi(3770)$ non-$D\bar{D}$ hadronic decay width stems from the difference between early total hadronic

and the D pair production cross section measurements: $\sigma(\psi(3770) \to D\bar{D}) = 5.0{\pm}0.5\,\mathrm{nb}$, $\sigma(\psi(3770) \to hadrons) = 7.8{\pm}0.8\,\mathrm{nb}$. This invites the the following set of questions: Which non-$D\bar{D}$ channels are available to $\psi(3770)$ decay? Can the measurement of the total hadronic cross section be confirmed? Can the measurement of the D-pair production cross section be confirmed?

As to the last question, preliminary measurements seem to indicate a higher D-pair production cross section: $\sigma(\psi(3770) \to D\bar{D})^{CLEO} = (5.78 \pm 0.11 \pm 0.38)\,\mathrm{nb}$, $\sigma(\psi(3770) \to D\bar{D})^{BES} = (6.51 \pm 0.44 \pm 0.39)\,\mathrm{nb}$. The experimental techniques are somewhat different in that BES tags one of the D mesons, thereby gaining statistical advantage, while CLEO tags both D mesons, resulting in independence from external branching fractions. While there is an indication that the gap might not be as wide as previously thought, about 20% of the total width of $(23.6 \pm 2.7)\,\mathrm{MeV}$ [5] remain currently unaccounted for. Convincing unanimous evidence for what this gap is filled by has yet to be presented. The BES collaboration measured $\mathcal{B}(\psi(3770) \to \pi^+\pi^- J/\psi) = (0.34 \pm 0.14 \pm 0.08)\%$ or $\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) = (80 \pm 32 \pm 21)\,\mathrm{keV}$, which is to be compared with an upper limit set by CLEO of $\mathcal{B}(\psi(3770) \to \pi^+\pi^- J/\psi) < 0.26\%$ (90% CL). However, this channel, even if contributing of the order of 100 keV to the decay width, will not be able to account for the discrepancy previously observed. Radiative $\psi(3770)$ decays are estimated to amount to at most a few hundred keV. In addition, the question whether or not there are hadronic non-$D\bar{D}$ decays of the $\psi(3770)$ is interesting in the context of mixing scenarios. If mixing is at work, the modes expected from J/ψ that seem suppressed at the $\psi(2S)$ can give rise to a partial width at the $\psi(3770)$. An improved understanding of $\psi(2S)$ decays will aid in settling this question.

3.2 Decay into lepton pairs [6]

Studying bottomonium decay into lepton pairs provides access to the total width, which at some 10 keV for the narrow $\Upsilon(1,2,3S)$ resonances is below the typical beam energy spread of an e^+e^- collider of a few MeV, through $\Gamma_{tot} = \Gamma_{\ell\ell}/\mathcal{B}_{\ell\ell}$. In practice, the most precise measurement comes from employing lepton universality and using Γ_{ee} together with $\mathcal{B}_{\mu\mu}$. Measurements of dilepton branching fractions are interesting in their own right to confront LQCD predictions (the precision of which has reached the percent level now), to test lepton universality, and to compare $\Gamma_{\ell\ell}$ with the hadronic widths $\Gamma_{ggg,\gamma gg,q\bar{q}}$.

CLEO studied $\Upsilon(1/2/3S) \to \mu^+\mu^-$ production using $1.1/1.2/1.2\,\mathrm{fb}^{-1}$ on-resonance and $0.19/0.44/0.16\,\mathrm{fb}^{-1}$ off-resonance data. The CLEO results, corrected for interference with continuum, are: $\mathcal{B}(\Upsilon(1/2/3S) \to \mu^+\mu^-)^{CLEO} = (2.49 \pm 0.02 \pm 0.07)/(2.03 \pm 0.03 \pm 0.08)/(2.39 \pm 0.07 \pm 0.10)\%$, to be compared with the PDG values of [5] $(2.48 \pm 0.06)/(1.31 \pm 0.21)/(1.81 \pm 0.17)\%$. This illustrates that the desired precision to keep up with progress in Lattice QCD has been reached. Since the CLEO $\mathcal{B}(\Upsilon(2,3S)$ are found to be substantially higher, thereby reducing the total width by the same percentage, predictions for cascade decays such as $\Upsilon(3S) \to \gamma\chi_{bJ} \to \gamma\gamma\Upsilon(2S)$ are bound to change.

3.3 Baryon pair production in J/ψ and χ_{cJ} decays [7]

BES used their 58M J/ψ sample to measure $\mathcal{B}(J/\psi \to p\bar{p}) = (2.26{\pm}0.01{\pm}0.14)$. This is the single most precise measurement of this branching fraction to date. The angular distribution is fit with the expression $dN/d\cos\theta_p = 1 + \alpha_p \cos^2\theta_p$, where θ_p is the angle between the proton and the beam direction. Neglecting baryon and quark masses one would expect $\alpha = 1$ for all baryons; including masses yields $\alpha_p = 0.66$ and $\alpha_\Lambda = 0.51$. The experimental results are $\alpha_p^{exp} = 0.676 \pm 0.036 \pm 0.042$ and $\alpha_\Lambda^{exp} = 0.52 \pm 0.33 \pm 0.13$, in agreement with the prediction. Proton pairs are produced about twice as copiously in J/ψ decays as $\Lambda\bar{\Lambda}$ pairs. In $\psi(2S)$ decays, their branching fractions are comparable.

Baryon pairs from χ_{cJ} decay can be observed through $\psi(2S) \to \gamma\chi_{cJ} \to \gamma B\bar{B}$ and compared with the Color Octet Model prediction that one should expect half as many $\Lambda\bar{\Lambda}$ events as $p\bar{p}$ events. These have been made based on $\chi_{cJ} \to p\bar{p}$ measurements, which they describe well, and then generalized to other baryons. The BES $\chi_{cJ} \to \Lambda\bar{\Lambda}$ results from 14M $\psi(2S)$ decays indicated an excess over this prediction by about a factor of two rather than a suppression, which has been confirmed as the branching fractions $\mathcal{B}(\chi_{cJ} \to p\bar{p})$ have been remeasured.

3.4 "Heavy to Heavy": Charmonium in $\Upsilon(1S)$ Decays [8]

The Color Octet Mechanism (COM) $b\bar{b} \to gc\bar{c}$, $ggc\bar{c}$ was employed to explain J/ψ production rates that could not be attributed to the thus far successful Color Singlet Model (CSM), which employs $b\bar{b} \to ggc\bar{c}c\bar{c}$. The two approaches predict different J/ψ momentum spectra as well as angular distributions and branching fractions for $\Upsilon(1S) \to J/\psi X$. A portion of the observed J/ψ signal

will be from $\Upsilon(1S) \to \psi(2S), \chi_{cJ} + X_1 \to J/\psi + X_2$ (not observed before). The magnitude of this feed-down contribution is also predicted by the two models.

A CLEO study of charmonium production in $\Upsilon(1S)$ data intends to shed additional light onto the question which mechanism is at work. Data taken on or near the $\Upsilon(4S)$ resonance is appropriately scaled and used to calculate the continuum background, which is small in comparison with the signal.

The inclusive branching fraction $\Upsilon(1S) \to J/\psi + X$ is measured to be $(6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$, in compliance with both COM and CSM predictions, both at about 6×10^{-4}. The process $\Upsilon \to \gamma^* \to q\bar{q} \to J/\psi + X$ is linked with the continuum process $e^+e^- \to \gamma^* \to q\bar{q} \to J/\psi + X$ and can thus be estimated relative to the process $\Upsilon \to ggg, gg\gamma \to J/\psi + X$. The sum of the gluonic reactions dominates at a ratio of about 9:1. Also, the J/ψ momentum spectrum, scaled according to J/ψ momentum $x = p_{J/\psi}/p_{max}$ to eliminate beam energy dependence, has been measured. The COM predicts a peak at the highest x values, whereas the CSM shows an accumulation around $x = 0.5$. The measured spectrum peaks at $x = 0.3$. The situation is complicated by the fact that final state interactions, which could in principle soften the predicted spectra somewhat, have not been taken into account in the predictions.

Other results of this work include the first determination of the branching fractions of and feed-down from $\Upsilon(1S) \to \psi(2S), \chi_{cJ} + X, J = 1, 2$, which is found to be a factor of two above both the CSM and the COM predictions. (Since $\mathcal{B}(\chi_{c0} \to J/\psi\gamma)$ is an order of magnitude smaller than $\mathcal{B}(\chi_{c[1,2]} \to J/\psi\gamma)$, the absence of a signal for χ_{c0} is not surprising.)

3.5 "Heavy To Light" Charmonium Decays [9)]

Decays of charmonia into light hadrons have often be studied in the light of the "12% rule". This is a scaling prescription connecting $\psi(2S)$ and J/ψ decays into hadronic final states. It allows one to compare the branching fraction ratio with that for decay into lepton pairs, which is measured to be 12% [5)]. Modifications to this simple picture arise from non-relativistic corrections, form factor dependence on the two different center-of-mass energies, powers of $\alpha_s(m_{\psi(2S)})/\alpha_s(m_{J/\psi})$, and many more. Exact agreement with the prediction is therefore not to be expected. However, even with a more generous view some modes exhibit a substantial suppression, such as $\rho\pi$ and K^*K. It has been conjectured that the suppression is related to quantum numbers and that

vector pseudoscalar final states might be especially affected. Also, interference with continuum could play an important role as for tiny branching fractions the resonant and non-resonant cross section may be of comparable magnitude. Finally, it is possible that the prescription only holds for electromagnetic processes ($c\bar{c} \to \gamma^* \to q\bar{q}$), but not for those mediated by decay into gluons. This would imply that isospin violating modes, where the otherwise dominant gluonic process is absent, are of special importance to study. A consistent picture has thus far not emerged, partly due to lack of experimental data.

CLEO and BES have brought forward new $\psi(2S) \to VP$ measurements. The most prominent channel is $\psi(2S) \to \rho\pi$, which constitutes a big branching fraction on the J/ψ. It is not understood why it is so rare in $\psi(2S)$ decays. Another interesting feature is the different population of the Dalitz plane from what is seen in continuum and J/ψ. These two show clear ρ bands over some non-resonant background, whereas $\psi(2S)$ decays appear to proceed dominantly non-resonantly. To determine what mechanism is at work, a partial wave analysis would be helpful, which is not possible with the data at hand.

4 Summary and Acknowledgements

Experimental progress continues in the area of heavy quarkonia, thereby adding puzzle pieces to our understanding of many aspects of QCD. It is to be hoped that with future larger data samples more precision studies become feasible and that the remaining undiscovered states disclose themselves.

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